Renewable and Sustainable Energy Reviews 15 (2011) 2779–2790

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part I: Methodology

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ARTICLE INFO

Article history:
Received 11 October 2010
Accepted 15 January 2011

Keywords:
Climate change
Adaptation planning
Decision making
Fuzzy sets
Uncertainty

ABSTRACT

In this study, a large-scale integrated modeling system (IMS) was developed for supporting climate-change impact analysis and adaptation planning under multi-level uncertainties. A number of methodologies were seamlessly incorporated within IMS, including fuzzy-interval inference method (FIIM), inexact energy model (IEM), and uncertainty analysis. The system could (i) encompass multiple technologies, energy resources, and sub-sectors, and climate change impact analysis into a general modeling framework, (ii) address interactions of climate change impacts on multiple energy sub-sectors and resources within an EMS, (iii) identify optimal adaptation strategies of an EMS to climate change impact through a two-step procedure, (iv) deal with multiple levels of uncertain information associated with processes of climate change impact analysis and adaptation planning, and (v) seamlessly combine climate change impact analysis results with inexact adaptation planning. It could provide decision makers a comprehensive view on the EMS as well as the corresponding adaptation schemes under climate change, greatly improving the robustness and completeness of the decision-making processes. The generated solutions can provide desired energy resource/service allocation with a minimized system cost, a maximized system reliability and a maximized energy security under varied climate change impact levels, as well as multiple levels of uncertainties. In a companion paper, the developed method is applied to a real case for the long-term planning of waste management in the Province of Manitoba, Canada.

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doi:10.1016/j.rser.2011.03.013

1. Introduction

Sustainable energy utilization has become a prominent policy target in many countries across the world [1,2]. However, there are many concerns over the adoption of various energy resources, such as energy-shortage risk, greenhouse gas emission, and renewable energy development, posing great challenges for decision makers in multi-scale energy management systems (EMSs). Also, the management efforts are complicated by climate change due to its significant effects on statistics of many energy sources (e.g., max, min, mean values and variance of hydropower, solar and wind energies). Moreover, such efforts are subject to multiple levels of uncertainties that are associated with the forecast of changing climatic conditions (e.g., uncertain shifts of precipitation patterns), the interactions between energy resources/technologies and climatic variations (e.g., uncertain fluctuation of hydropower generation in responding to precipitation variations), and the planning of EMSs (e.g., uncertain estimation of energy prices). This leads to a variety of complexities in relevant decision-making under climate change. These complexities may be further multiplied by multi-period, multi-facility and multi-objective features as well as system dynamics. Thus, system analysis techniques are desired to assist in formulating long-term energy management and allocation plans, which will be helpful not only for analyzing tradeoffs among various socio-economic, energy-related, and environmental objectives, but also for providing cost-effective adaptation schemes in responding to varied impact levels of climate change.

Previously, a plenty of efforts were undertaken for investigating impacts of climate change on multi-scale energy management systems and planning the corresponding adaptation capacities [3–13,74–78]. For instance, Peramunetilleke [5] assessed impacts of climate change on Sri Lanka's hydroelectric production. They believed that power supply from hydropower without back-up sources would be highly risky under extreme climatic events. Allen and Christensen [14] briefly reviewed the impacts of climate change and suggested that a diverse range of issues would contribute to this process. Sutherland [15] qualitatively analyzed potential impacts of climate change on a number of energy-intensive industries in US. Breslow and Sailor [16] investigated impacts of climate change on wind speeds and, hence, on wind power generation in US. A series of GCM outputs from the Canadian Climate Center and the Hadley Center were used for providing a range of possible variations in seasonal mean wind magnitude. Potential impacts of climate change on heating and cooling energy demands were investigated through building energy simulation models under hourly weather scenarios and were applied to the Zurich–Kloten area of Switzerland [17]. Gaterell and McEvoy [10] examined uncertain effects of climate change on performance of energy insulation measures. Christenson et al. [8] investigated impacts of climate change on energy demand of residential buildings through the degree-days method. A procedure to estimate heating and cooling degree-days from monthly temperature data was proposed, verified, and applied to four representative buildings in Switzerland. Mirasgedis et al. [18] adopted a regional climate model (i.e., PRECIS) to predict future climatic conditions under different emissions scenarios. The predicted data were used as inputs to a multiple-regression model to examine sensitivity of electricity demand in Greece's interconnected power system under various climatic and socio-economic conditions. Pryor and Barthelmie [19] qualitatively assessed impacts of climate change on wind energy sources, particularly on operation and maintenance of several wind farms. Based on a qualitative method, Whitmarsh [20] investigated various responses to the impacts of climate change in many energy management systems. Guan [21] attempted to evaluate impacts of climate change on building environment through combination of weather-data forecasting and building simulation techniques. Bassi and Baer [22] employed an integrated modeling approach to carry out a country-wide, cross-sector analysis of the interactions among Ecuador's energy, social, economic and environmental sectors under climate change. Isaac and van Vuuren [23] assessed potential energy consumptions for future residential heating and air conditioning under climate change.

Under a series of climate change impact levels, adaptation plans of EMSs need to be systematically considered by decision makers. Over the past two decades, a large number of studies were undertaken on adaptation planning toward climate change in environmental and energy management systems planning [24–50]. For example, Huang et al. [51] proposed an inexact-fuzzy multiobjective programming model for supporting adaptation planning of land resources management in Mackenzie Basin under changing climatic conditions. Stakhiv [52] suggested that policy makers and water resource managers should be aware of the evolving information on climate change impacts as an activity that was preparatory to sound decision making on current water resource management actions. Tol et al. [24] made a thorough investigation on studies related to climate change adaptation. They suggested that there should be four categories of adaptation measures toward climate change, including: no adaptation, arbitrary adaptation, observed adaptation, and modeled adaptation (optimization). Since climate change poses significant challenges for water resource management in Canada, de Loë et al. [53] discussed issues related to identification of adaptation measures to water supply systems in the near future. Næss et al. [33] examined the adaptation of infrastructural institutions under climate change in Norway. Two municipalities were used as examples for investigating institutional responses to floods under climate change. Dessai and Hulme [54] presented an assessment framework for identifying adaptation strategies that were robust (i.e., insensitive) to climate change uncertainties. The framework was applied to a real-world case for supporting water resources management in eastern England. Osbahr et al. [55] explored cross-scale dynamics in coping and adjusting responses toward climate change based on qualitative data from a real-world case in Mozambique. More recently, Hoffmann et al. [56] empirically examined the determinants of adaptation measures/policies toward climate change. They also analyzed the influence of possible climate change effects on the scope of adaptation measures through a number of linear regression models. Bryan et al. [41] analyzed the adaptation strategies of farmers in several countries and analyzed the factors influencing their decisions. Deressa et al. [57] identified major strategies used by farmers to adapt to climate change in Nile Basin of Ethiopia. They also analyzed the factors that might affect their choices of method and the barriers to adaptation.

Particularly, a number of studies were undertaken for examining potential adaptation strategies of energy sectors in many countries under climate change. For instance, Simeonova [58] complied and analyzed a variety of policies and measures for adapting to climate change in the energy sectors of many central and eastern European countries. Matondo et al. [59] examined the impacts of climate change on hydrological regimes, water resources management, and hydropower generation. Ruth and Lin [60] explored potential impacts of climate change on consumptions of natural gas, electricity, and heating oil by residential and commercial sectors in the state of Maryland of the US. Time series analysis was then used to quantify relationships between historical temperature and energy demand. A dynamic computer model based on those relationships was used for simulating future energy demand under a range of energy prices, temperatures, and other driving factors. Mansur et al. [61] adopted a national energy model of fuel choice to generate climate change adaptation strategies at both households and firm scales. They suggested that increasing electricity consumption for space cooling would be observed with a

reduction in energy consumption for space heating under climate change. Overall, energy-related expenditures would likely increase in America due to the impacts of climate change on residential heating and cooling, resulting in potential welfare damages. Jenkins et al. [62] attempted to quantify how climate change will have a direct effect on heating and cooling energy use in future office environments. The results confirmed the importance of demand-side management before assessing the supply-side opportunities under extreme climatic events. The study also highlighted the importance and possibilities, of adaptation strategies to future climates, and the benefits of promoting heating-dominated buildings instead of cooling-dominated ones. Weisser et al. [63] used a qualitative analysis method to explore the conditions under which nuclear power could adapt to climate change over a long term period.

Previous studies on climate change impact analysis related to EMSs are mostly based on qualitative methods, and, thus, could merely generate qualitative information. Many studies were conducted to analyze the impacts of climate change on energy sectors as well as to examine the corresponding adaptation strategies through integrating many quantitative methods and/or GCM/RCM results. However, direct incorporation of GCM/RCM results into climate-change impact analysis for multi-scale EMSs was limited to one or several climatic sensitive parameters such as temperature, precipitation, and humidity, which might be unreasonable in realistic problems. In addition, most of the previous studies focused on impacts of climate change on an individual energy sub-sector, process or technology (e.g., residential, commercial and hydropower generation sub-sectors). There was a lack of studies that could comprehensively reflect and analyze impacts of climate change on multiple energy sub-sectors and technologies, and thus analyze the impacts from an entire EMS point of view. Moreover, the process of impact analysis involved multiple levels of imprecise information, which was largely neglected in the previous studies. In fact, the process of climate change impact analysis is subject to a variety of uncertainties. For example, in most of the quantitative or semi-quantitative methods based on GCM/RCM results, there are multiple formats of uncertainties embedded within not only the input information, but also the weather-forecasting mechanisms. Furthermore, impact analysis could merely provide answers to the question of “which sector/process within an energy management system would be the most vulnerable under climate change”. Decision makers may need to know “if there is any necessity to take adaptation actions” and “what the optimal adaptation actions for the energy sector under multiple system uncertainties will be”. The questions need to be answered through EMSs adaptation planning. Likewise, in the process of adaptation planning based on optimization models, relevant parameters and coefficients may be subject to multiple formats of uncertainties (e.g., intervals, probabilistic and possibilistic distributions). Until now, there were no reported studies that could link adaptation planning with climate-change impact analysis and could address multi-level uncertainties associated with impact analysis as well as the subsequent adaptation planning process. Therefore, an integrated modeling system for seamlessly coupling climate change impacts with EMSs adaptation planning is desired, particularly for a region that is heavily dependent on renewable energy resources and is, thus, vulnerable to climate change.

2. Methodology

2.1. A systematic perspective on adaptation planning under climate change

Almost all energy-related processes and factors would be directly and/or indirectly influenced by changing climatic conditions (Fig. 1). Among them, end-user demands, renewable energy resources and the corresponding utilization facilities would probably be the most sensitive and vulnerable ones. For instance, availabilities of renewable energy resources (e.g., hydropower and wind energy) are highly dependent on the statistics (e.g., min, peak and mean values as well as variance) of many meteorological variables that might fluctuate within a certain range due to climate change. Such variations of renewable energy availabilities would then affect operating statuses of relevant facilities, resulting in changes in their energy outputs. Similarly, in responding to variations of climatic factors/conditions, such as temperature, solar radiation, and humidity, end-user demands for space heating, water heating, and space cooling would correspondingly vary over a certain range. Apparently, these impacts would not affect an individual energy sub-sector (e.g., energy demand and production) in a separate way. Instead, they interact with each other and, thus, would cause an integrated impact on the entire EMS. Such an integrated impact over a long-term planning period needs to be systematically analyzed by decision makers in order to discern the most optimal adaptation schemes for the entire EMS under climate change. However, such a task is difficult due to a variety of uncertainties associated with changing climatic conditions as well as decision makers' subjective judgments on impacts. For example, due to the lack of sufficient information related to the evaluation guidelines (e.g., impact levels), fuzziness is always associated with the process of impact identification and integration, which is normally caused by vague and imprecise linguistic terms. Correspondingly, the evaluation of occurrence chances of climate change and their consequences on EMSs is also subject to uncertainties and is difficult to be handled through conventional methods. This implies that planning activities for EMSs would be misled into a deviated or even false direction without a comprehensive consideration over the integrated impacts of climate change.

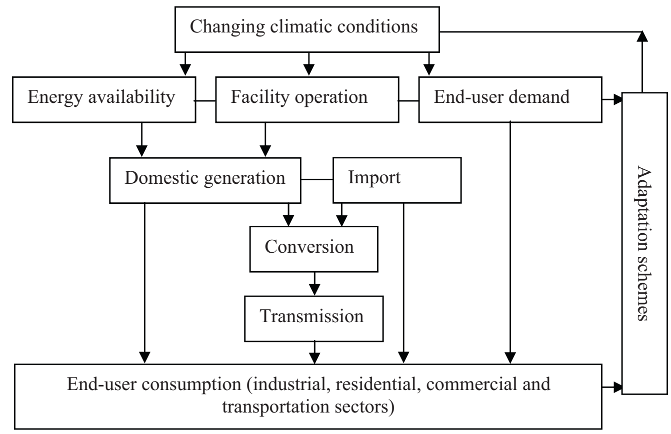

Fig. 1. Climate change impacts and adaptation schemes of EMSs.

Moreover, there is a variety of uncertain information associated with decision process, which can only be expressed as interval numbers without known distributions. Such uncertain information need to be effectively incorporated into the planning process and the obtained decision alternatives, which represents a different level of uncertainties compared with those implied in climate change analysis. Therefore, in this research, the integrated climate change impacts will be incorporated into the modeling framework to facilitate identifying adaptation plans with increased robustness under various changing conditions. Specifically, a fuzzy-interval inference method (FIIM) and an inexact energy model (IEM) will be developed and then integrated into a general modeling system (IEMS) as well as applied to the province of Manitoba (IEMS-Manitoba, presented in a companion paper).

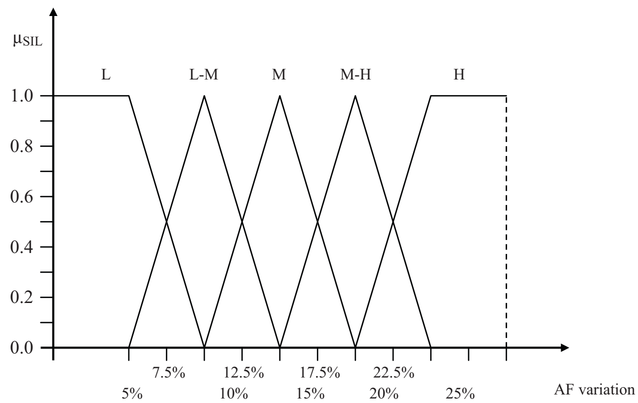

Fig. 2. Membership function of climate change impacts on energy supply (i.e., renewable availability factors based on renewable energy resources). *Note*: AF = availability factor.

2.2. Coupled climate-change impact analysis under uncertainty

2.2.1. Impacts on energy supply

Considering an EMS wherein electricity production mainly occurs based on renewable energy resources such as hydropower and wind energy, over a long-term period, climate change will have direct impacts on the availability of these resources due to potential variations in many climatic factors and conditions such as precipitation types, radiation intensities, and wind speeds. Consequently, the changes in resource availability would affect operation statuses of relevant electricity generation facilities. In this research, an availability factor is introduced, which is defined as the amount of time that a hydroelectric power station (or wind farm) needs to produce electricity over a certain period, divided by the total time of this period. Then, five fuzzy sets are assigned to represent different levels of impacts of climate change on the availability factors of renewable-energy-based power generation facilities, corresponding to "low impact", "low-to-medium impact", "medium impact", "medium-to-high impact" and "high impact". The construction of membership functions for these five fuzzy sets relies on the expertise and experience of experts and stakeholders. The involved experts and stakeholders should have in-depth knowledge about the province and the energy management system, and can, thus, provide valuable inputs for quantifying the uncertainties [64,65]. Fuzzy logic is then employed for processing such subjective opinions.

In this study, fuzzy sets corresponding to different levels of climate change impacts were obtained through questionnaire surveys. Forty-eight persons were interviewed about their opinions on the corresponding relations between climate change impact levels and renewable energy availability factor decrements. As listed in Table 1, 54.10% of the surveyed respondents believed that "low impact" should correspond to the statement "the availability factor of a renewable-energy-based power generation facility will decrease by 5.00% or less"; 58.40% of the respondents selected: "the availability factor of a renewable-energy-based power generation facility will decrease by approximately 10%" as "low-to-medium impact"; 58.40% of the respondents agreed that "the availability factor of a renewable-energy-based power generation facility will decrease by around 15.00%" represents "medium impact"; 60.40% of the respondents matched "the availability factor of a renewable-energy-based power generation facility will decrease by approximately 20.00%" with "medium-to-high impact"; and 77.10% of the respondents considered "the availability factor of a renewable-energy-based power generation facility will decrease 25.00% or more" as "high impact". According to Hwang and Chen [66], the membership functions of these fuzzy sets can then be constructed based on above investigation results. The constructed fuzzy sets are displayed in Fig. 2. In this figure, "L", "L-M", "M", "M-H" and "H" represent low, low-to-medium, medium, medium-to-high, and high impacts, respectively.

Table 1
Impacts of climate change on energy supply (power generation from renewable energy resources).

The availability factor of renewable energy resources will decrease by approximately:	No. of respondents	Percentage (%)
Low impacts		
1% or less	0	0.00
2% or less	0	0.00
3% or less	13	27.10
4% or less	9	18.80
5% or less	26	54.10
6% or less	0	0.00
7% or less	0	0.00
8% or less	0	0.00
9% or less	0	0.00
Total no. of respondents	48	100.00
Low-to-Medium impacts		
5%	0	0.00
6%	0	0.00
7%	0	0.00
8%	10	20.80
9%	10	20.80
10%	28	58.40
15%	0	0.00
20%	0	0.00
25%	0	0.00
Total no. of respondents	48	100.00
Medium impacts		
5%	0	0.00
6%	0	0.00
7%	0	0.00
8%	0	0.00
9%	10	20.80
10%	10	20.80
15%	28	58.40
20%	0	0.00
25%	0	0.00
Total no. of respondents	48	100.00
Medium-to-High impacts		
5%	0	0.00
6%	0	0.00
7%	0	0.00
8%	0	0.00
9%	0	0.00
10%	6	12.50
15%	13	27.10
20%	29	60.40
25%	0	0.00
Total no. of respondents	48	100.00
High impacts		
5% or greater	0	0.00
6% or greater	0	0.00
7% or greater	0	0.00
8% or greater	0	0.00
9% or greater	0	0.00
10% or greater	0	0.00
15% or greater	0	0.00
20% or greater	11	22.90
25% or greater	37	77.10
Total no. of respondents	48	100.00

Table 2
Climate change impacts on end-user energy demands (heating and cooling).

Energy demands for heating and cooling will increase by approximately:	No. of respondents	Percentage (%)
Low impacts		
1% or less	23	47.90
1.5% or less	14	29.20
2.0% or less	11	22.90
2.5% or less	0	0.00
3.0% or less	0	0.00
3.5% or less	0	0.00
4.0% or less	0	0.00
4.5% or less	0	0.00
5.0% or less	0	0.00
Total no. of respondents	48	100.00
Low-to-Medium impacts		
1%	0	0.00
1.5%	6	12.50
2.0%	19	39.60
2.5%	15	31.20
3.0%	7	14.60
3.5%	0	0.00
4.0%	0	0.00
4.5%	0	0.00
5.0%	0	0.00
Total no. of respondents	48	100.00
Medium impacts		
1%	0	0.00
1.5%	0	0.00
2.0%	2	4.20
2.5%	10	20.80
3.0%	21	43.80
3.5%	11	22.90
4.0%	4	8.30
4.5%	0	0.00
5.0%	0	0.00
Total no. of respondents	48	100.00%
Medium-to-High impacts		
1%	0	0.00
1.5%	0	0.00
2.0%	0	0.00
2.5%	1	2.00
3.0%	8	16.70
3.5%	14	29.20
4.0%	21	43.80
4.5%	4	8.30
5.0%	0	0.00
Total no. of respondents	48	100.00
High impacts		
1% or greater	0	0.00
1.5% or greater	0	0.00
2.0% or greater	0	0.00
2.5% or greater	0	0.00
3.0% or greater	0	0.00
3.5% or greater	1	2.00
4.0% or greater	3	6.30
4.5% or greater	21	43.80
5.0% or greater	23	47.90
Total no. of respondents	48	100.00

2.2.2. Impacts on energy demand

Similar to the availabilities of renewable energy resources, energy demands are also sensitive to the variations in climatic conditions, especially those for heating and cooling in residential and commercial sectors [67,68,73]. Similar to the identification of climate change impacts on energy supply, the impacts on end-user energy demands are also categorized into five levels (i.e., low, low-to-medium, medium, medium-to-high, and high) which

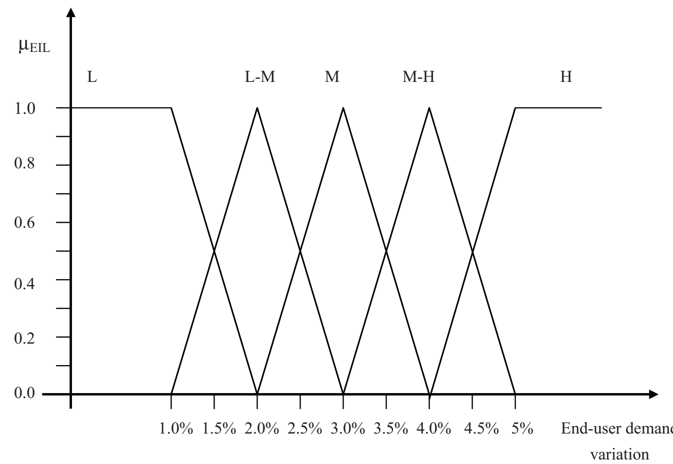

Fig. 3. Membership function of the climate change impacts on end-user energy demand.

are presented as five fuzzy sets. A survey was conducted to obtain the associated membership functions. The energy demands were assumed to increase by 1.00–5.00% compared to the original amounts. The survey results, listed in Table 2 suggest that: "energy demands for heating and cooling in the residential and commercial sectors will increase by approximately 1.00% or less" corresponds to "low impact"; "energy demands for heating and cooling in residential and commercial sectors will increase by approximately 1.50%" corresponds to "low-to-medium impact"; "energy demands for heating and cooling in residential and commercial sectors will increase by approximately 2.00%" corresponds to "medium impact"; "energy demands for heating and cooling in residential and commercial sectors will increase by approximately 2.50%" corresponds to "medium-to-high impact"; "energy demands for heating and cooling in residential and commercial sectors would increase approximately 3.00% or more" corresponds to "high impact". Fuzzy membership functions associated with these five impact levels are established according to the above investigation results (Fig. 3).

2.2.3. Coupled impacts on energy management systems

In order to comprehensively investigate the impacts of climate change on the entire EMS, integrated impact levels are derived from combining those impacts on both energy supply and end-user demand sub-sectors. However, it is very hard to link climate impacts on both sides through conventional quantitative methods. Therefore, fuzzy logic could be an effective tool for facilitating the quantification of such integrated impacts, leading to the development of a fuzzy-interval inference method (FIIM).

In this study, the determination of the integrated impact levels will be based on a series of fuzzy rules from experts and stakeholders. The impact levels were set to include six categories, namely, "low", "low-to-medium", "medium", "medium-high", "high" and "very-high". The six levels are expressed as six fuzzy sets. Then, the fuzzy logic operator "AND" is used to join factors in the antecedents of the rules. Since both environmental and health risks include five categories of fuzzy events, there will be a total of 150 rules ($5 \times 5 \times 6$). Assume that, if a rule achieves the highest frequency in the survey, then it will be kept in the rule base for the determination of the integrated impact level. It was found that 68.30% of the surveyed respondents selected "if both impacts on demand and supply are low, then the integrated impact will be low"; 78.50% selected "if the impacts on supply side is low and demand side is low-to-medium, then the integrated impact level will be low-to-medium"; 76.80% chose "if the impact on energy supply is low and

Table 3
Rules for the coupled climate change impact level.

No.	Antecedent		Then the integrated impact is					
	If impacts on renewable energy availability factor is	And impacts on end-user demands is	L	L-M	M	M-H	H	VH
1	Low	Low	√					
2	Low	Low-to-Medium		√				
3	Low	Medium			√			
4	Low	Medium-to-High				√		
5	Low	High					√	
6	Low-to-Medium	Low		√				
7	Low-to-Medium	Low-to-Medium		√				
8	Low-to-Medium	Medium			√			
9	Low-to-Medium	Medium-to-High				√		
10	Low-to-Medium	High					√	
11	Medium	Low			√			
12	Medium	Low-to-Medium			√			
13	Medium	Medium			√			
14	Medium	Medium-to-High				√		
15	Medium	High					√	
16	Medium-to-High	Low					√	
17	Medium-to-High	Low-to-Medium					√	
18	Medium-to-High	Medium					√	
19	Medium-to-High	Medium-to-High					√	
20	Medium-to-High	High						√
21	High	Low					√	
22	High	Low-to-Medium					√	
23	High	Medium					√	
24	High	Medium-to-High					√	
25	High	High						√

Note: L = Low; L-M = Low-to-Medium; M = Medium; M-to-H = Medium-to-High; H = High; VH = Very High.

the one on energy demand is medium, then the integrated impact will be medium"; 83.60% selected "if the impact on energy supply is low and the one on energy demand is medium-to-high, then the integrated impact will be medium-to-high"; 70.50% selected "if the impact on energy supply is low and the one on energy demand is high, then the integrated impact will be high" (Table 3).

Since the integrated impact level can be categorized into "low", "low-to-medium", "medium", "medium-high", "high" and "very-high", the corresponding membership functions of these fuzzy events can then be established according to Hwang and Chen [62] (Fig. 4). The range of the integrated impact levels is subjectively assigned with a range of [0,100]. Thus, they will have single numerical site scores after defuzzification. These numerical values have no direct relationship with the values of the input impact factors (e.g., climate change impact levels of both energy supply and demand sides). However, after establishing the fuzzy sets of the integrated impact level, a numerical site score can be obtained from Fig. 4 through the fuzzy "AND" or fuzzy "OR" operations based on the two-side impact levels. This will be illustrated in the following case study. The site management decisions can then be made based on the calculated site scores that describe the general risk level. Table 4 lists the relationship between site scores and suggested management actions.

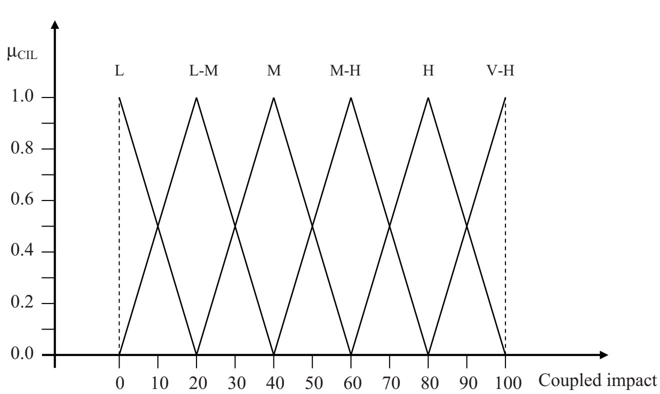

Fig. 4. Membership functions of integrated climate change impact levels on energy management systems.

2.3. Adaptation planning under uncertainty

The results of integrated climate change impact analysis can only provide information related to "how serious will climate change affect the EMS?" to decision makers. Decision makers probably need to know "how and when to take adaptation actions toward climate change?" Therefore, it is desired to couple the impact analysis results with adaptation planning efforts. Also, uncertainties associated with parameter/coefficients of adaptation planning need to be dealt with. Thus, an inexact optimization approach will be adopted. In this research, an inexact energy model (IEM) will be developed for supporting long-term energy management systems planning under the business as usual (BAU) case, as well as adaptation planning under climate change. A number of issues concerning cost-effective allocation of energy resources, technologies, activities and investments can, thus, be addressed. It is expected that the results could provide useful information and decision support for energy management systems planning within a provincial context. IEM is a large-scale dynamic programming model for energy systems planning under uncertainty and complexity. This model is subject to a number of constraints, such as end-user demand, economic cost and energy availability. It

Table 4
General adaptation strategies under coupled climate change impacts.

Calculated score	Adaptation planning measures
90–100	Immediate actions need to be taken for mitigating climate change impacts on energy management systems
70–90	Take full actions for mitigating climate change impacts on energy management systems
50–70	Restrict energy export and consumption
30–50	Take interim control measures
10–30	Effects of climate change on energy management systems should be monitored

can be used to describe detailed characteristics of energy-related technologies and evaluate economic and environmental effects of relevant policies and regulations. Such an energy management system can be characterized as a network/chain of energy flows, starting from energy-supply options (such as energy production, export, and import) and ending in end-use sectors (such as residential, commercial, industrial, and transportation sectors). It can also be customized into several sub-sectors based on site-specific features when it is applied to real-world cases such as in Province of Manitoba.

With consideration of local energy management policies, the objective function is to minimize the total costs associated with energy services, activities and investments in the study province over the entire planning horizon. This objective function is a combination of costs associated with a variety of processes that move energy from production and conversion to consumption. The cost of each process is further divided into sub-costs, such as costs of energy resource supply, energy process/conversion, technology investment, and environmental management. Decision variables in IEM represent key discrete points of energy activities. Electricity generated from different facilities, production capacities of energy generation facilities, volumes of oil imported, and gasoline consumed by private automobiles can be examples of discrete variables. The constraints include the relationships among decision variables, energy production efficiencies, capital costs, investment costs, and energy availabilities. Also, in order to address uncertainties associated with many factors/processes within an EMS and can be expressed as interval numbers, an inexact programming method is adopted. The model is based on the interval-parameter linear programming (ILP) model, in which the uncertain parameters are expressed as intervals without any distributional information that is always required in fuzzy and stochastic programming. The ILP allows the interval information to be directly communicated into the optimization process and resulting solution [69]. According to Huang et al. [70–72], an ILP model can be written as follows:

$$\mathrm{Min} f^{\pm} = \mathbf{C}^{\pm}\mathbf{X}^{\pm} \tag{1a}$$

subject to:

$$\mathbf{A}^{\pm}\mathbf{X}^{\pm} \le \mathbf{B}^{\pm} \tag{1b}$$

$$\mathbf{X}^{\pm} \ge 0 \tag{1c}$$

where $\mathbf{A}^{\pm} \in \{\mathrm{R}^{\pm}\}^{m\times n}$, $\mathbf{B}^{\pm} \in \{\mathbf{R}^{\pm}\}^{m\times 1}$, $\mathbf{C}^{\pm} \in \{\mathbf{R}^{\pm}\}^{1\times n}$, $\mathbf{X}^{\pm} \in \{\mathbf{R}^{\pm}\}^{n\times 1}$, and $\mathbf{R}^{\pm}$ denotes a set of interval numbers.

Thus, IEM can be formulated as follows:

$$\text{Objective function}: Min f^{\pm} = \sum_{i=1}^{I}\sum_{t=1}^{T} C_{i,t}^{\pm} \tag{2a}$$

(1) The total cost of energy consumption in the residential sub-sector

$$\sum_{t=1}^{T} C_{1,t}^{\pm} = c_{1,1}^{\pm} + c_{1,2}^{\pm} + c_{1,3}^{\pm} + c_{1,4}^{\pm} + c_{1,5}^{\pm} \tag{2b}$$

(1a) Sub-cost of natural gas consumption in the residential sub-sector

$$c_{1,1}^{\pm} = \sum_{t=1}^{T} Rt_{1,1,t}^{\pm}(X_{1,1,1,t}^{\pm} + X_{1,1,4,t}^{\pm} + X_{1,1,5,t}^{\pm} + X_{1,1,6,t}^{\pm}) \tag{2c}$$

(1b) Sub-cost of fuel oil consumption in the residential sub-sector

$$c^{\pm} = \sum_{t=1}^{T} Rt_{1,2,t}^{\pm}(X_{1,2,1,t}^{\pm} + X_{1,2,3,t}^{\pm} + X_{1,2,4,t}^{\pm}) \tag{2d}$$

(1c) Sub-cost of liquefied petroleum gas (LPG) consumption in the residential sub-sector

$$c_{1,3}^{\pm} = \sum_{t=1}^{T} Rt_{1,3,t}^{\pm}(X_{1,3,1,t}^{\pm} + X_{1,3,3,t}^{\pm} + X_{1,3,4,t}^{\pm} + X_{1,3,5,t}^{\pm} + X_{1,3,6,t}^{\pm}) \tag{2e}$$

(1d) Sub-cost of heating oil consumption in the residential sub-sector

$$c_{1,4}^{\pm} = \sum_{t=1}^{T} Rt_{1,4,t}^{\pm}(X_{1,4,1,t}^{\pm} + X_{1,4,4,t}^{\pm}) \tag{2f}$$

(1e) Sub-cost of renewable energy resources consumption in the residential sub-sector

$$c^{\pm} = \sum_{t=1}^{T} Rt_{1,5,t}^{\pm}(X_{1,5,1,t}^{\pm} + X_{1,5,2,t}^{\pm} + X_{1,5,4,t}^{\pm} + X_{1,5,6,t}^{\pm}) \tag{2g}$$

(1f) Sub-cost of electricity consumption in the residential sub-sector

$$c_{1,6}^{\pm} = \sum_{t=1}^{T} Rt_{1,6,t}^{\pm}(X_{1,6,1,t}^{\pm} + X_{1,6,3,t}^{\pm} + X_{1,6,4,t}^{\pm} + X_{1,6,5,t}^{\pm} + X_{1,6,6,t}^{\pm}) \tag{2h}$$

(2) The total cost of energy consumption in the commercial sub-sector

$$\sum_{t=1}^{T} C_{2,t}^{\pm} = c_{2,1}^{\pm} + c_{2,2}^{\pm} + c_{2,3}^{\pm} + c_{2,4}^{\pm} + c_{2,5}^{\pm} + c_{2,6}^{\pm} \tag{2i}$$

(2a) Sub-cost of natural gas consumption in the commercial sub-sector

$$c_{2,1}^{\pm} = \sum_{t=1}^{T} Rt_{2,1,t}^{\pm}(X_{2,1,1,t}^{\pm} + X_{2,1,3,t}^{\pm} + X_{2,1,6,t}^{\pm}) \tag{2j}$$

(2b) Sub-cost of fuel oil consumption in the commercial sub-sector

$$c_{2,2}^{\pm} = \sum_{t=1}^{T} Rt_{2,2,t}^{\pm}(X_{2,2,1,t}^{\pm} + X_{2,2,3,t}^{\pm} + X_{2,2,4,t}^{\pm} + X_{2,2,6,t}^{\pm}) \tag{2k}$$

(2c) Sub-cost of LPG consumption in the commercial sub-sector

$$c^{\pm} = \sum_{t=1}^{T} Rt_{2,3,t}^{\pm}(X_{2,3,1,t}^{\pm} + X_{2,3,3,t}^{\pm} + X_{2,3,5,t}^{\pm} + X_{2,3,6,t}^{\pm}) \tag{2l}$$

(2d) Sub-cost of heating oil consumption in the commercial sub-sector

$$c_{2,4}^{\pm} = \sum_{t=1}^{T} Rt_{2,4,t}^{\pm}(X_{2,4,1,t}^{\pm} + X_{2,4,3,t}^{\pm}) \tag{2m}$$

(2e) Sub-cost of renewable energy resources consumption in commercial sub-sector

$$c_{2,5}^{\pm} = \sum_{t=1}^{T} Rt_{2,5,t}^{\pm}(X_{2,5,1,t}^{\pm} + X_{2,5,3,t}^{\pm} + X_{2,5,6,t}^{\pm}) \tag{2n}$$

(2f) Sub-cost of electricity consumption in commercial sub-sector

$$c^{\pm} = \sum_{t=1}^{T} Rt_{2,6,t}^{\pm}(X_{2,6,1,t}^{\pm} + X_{2,6,2,t}^{\pm} + X_{2,6,3,t}^{\pm} + X_{2,6,4,t}^{\pm} + X_{2,6,5,t}^{\pm} + X_{2,6,6,t}^{\pm}) \tag{2o}$$

(3) The total cost of energy consumption in the transportation sub-sector

$$\sum_{t=1}^{T} C_{3,t}^{\pm} = c_{3,1}^{\pm} + c_{3,2}^{\pm} + c_{3,3}^{\pm} + c_{3,4}^{\pm} + c_{3,5}^{\pm} + c_{3,6}^{\pm} + c_{3,7}^{\pm} \tag{2p}$$

(3a) Sub-cost of natural gas consumption in the transportation sub-sector

$$c^{\pm} = \sum_{t=1}^{T} Rt_{3,1,t}^{\pm}(X_{3,1,1,t}^{\pm} + X_{3,1,2,t}^{\pm} + X_{3,1,3,t}^{\pm} + X_{3,1,4,t}^{\pm} + X_{3,1,5,t}^{\pm} + X_{3,1,6,t}^{\pm}) \tag{2q}$$

(3b) Sub-cost of fuel oil consumption in the transportation sub-sector

$$c_{3,2}^{\pm} = \sum_{t=1}^{T} Rt_{3,2,t}^{\pm}(X_{3,2,5,t}^{\pm} + X_{3,2,6,t}^{\pm} + X_{3,2,7,t}^{\pm}) \tag{2r}$$

(3c) Sub-cost of LPG consumption in the transportation sub-sector

$$c_{3,3}^{\pm} = \sum_{t=1}^{T} Rt_{3,3,t}^{\pm}(X_{3,3,1,t}^{\pm} + X_{3,3,2,t}^{\pm} + X_{3,3,3,t}^{\pm} + X_{3,3,5,t}^{\pm}) \tag{2s}$$

(3d) Sub-cost of diesel consumption in the transportation sub-sector

$$c_{3,4}^{\pm} = \sum_{t=1}^{T} Rt_{3,4,t}^{\pm}(X_{3,4,1,t}^{\pm} + X_{3,4,2,t}^{\pm} + X_{3,4,3,t}^{\pm} + X_{3,4,5,t}^{\pm} + X_{3,4,6,t}^{\pm}) \tag{2t}$$

(3e) Sub-cost of jet fuel consumption in the transportation sub-sector

$$c^{\pm} = \sum_{t=1}^{T} Rt_{3,5,t}^{\pm} X_{3,5,4,t}^{\pm} \tag{2u}$$

(3f) Sub-cost of gasoline consumption in the transportation sub-sector

$$c_{3,6} = \sum_{t=1}^{T} Rt_{3,6,t}^{\pm}(X_{3,6,1,t}^{\pm} + X_{3,6,2,t}^{\pm} + X_{3,6,3,t}^{\pm} + X_{3,6,5,t}^{\pm} + X_{3,6,6,t}^{\pm}) \tag{2v}$$

(3g) Sub-cost of electricity consumption in the transportation sub-sector

$$c_{3.7}^{\pm} = \sum_{t=1}^{T} Rt_{3,7,t}^{\pm}(X_{3,7,1,t}^{\pm} + X_{3,7,3,t}^{\pm} + X_{3,7,4,t}^{\pm} + X_{3,7,5,t}^{\pm} + X_{3,7,6,t}^{\pm}) \tag{2w}$$

(4) The total cost of energy consumption in the industrial sub-sector

$$\sum_{t=1}^{T} C_{4,t}^{\pm} = c_{4,1}^{\pm} + c_{4,2}^{\pm} + c_{4,3}^{\pm} + c_{4,4}^{\pm} + c_{4,5}^{\pm} \tag{2x}$$

(4a) Sub-cost of natural gas consumption in the industrial sub-sector

$$c_{4,1}^{\pm} = \sum_{m}^{M}\sum_{t=1}^{T} Rt_{4,1,t}^{\pm} X_{4,1,m,t}^{\pm} \tag{2y}$$

(4b) Sub-cost of fuel oil consumption in the industrial sub-sector

$$c_{4,2}^{\pm} = \sum_{m}^{M}\sum_{t=1}^{T} Rt_{4,2,t}^{\pm} X_{4,2,m,t}^{\pm} \tag{2z}$$

(4c) Sub-cost of LPG consumption in the industrial sub-sector

$$c_{4,3}^{\pm} = \sum_{m}^{M}\sum_{t=1}^{T} Rt_{4,3,t}^{\pm} X_{4,3,m,t}^{\pm} \tag{2aa}$$

(4d) Sub-cost of coal consumption in the industrial sub-sector

$$c_{4,4}^{\pm} = \sum_{t=1}^{T} Rt_{4,4,t}^{\pm}(X_{4,4,1,t}^{\pm} + X_{4,4,3,t}^{\pm} + X_{4,4,5,t}^{\pm} + X_{4,4,6,t}^{\pm}) \tag{2ab}$$

(4e) Sub-cost of renewable energy resources consumption in the industrial sub-sector

$$c_{4,5}^{\pm} = \sum_{m}^{M}\sum_{t=1}^{T} Rt_{4,5,t}^{\pm} X_{4,5,m,t}^{\pm} \tag{2ac}$$

(4f) Sub-cost of electricity consumption in the industrial sub-sector

$$c_{4,6}^{\pm} = \sum_{m}^{M}\sum_{t=1}^{T} Rt_{4,6t}^{\pm} X_{4,6,m,t}^{\pm} \tag{2ad}$$

(5) The total cost of power generation facilities

$$\sum_{t=1}^{T} c^{\pm} = \sum_{n=1}^{N}\sum_{t=1}^{T} \left[\left(\mathrm{AFOM}_{n,t}^{\pm} + \mathrm{AVOM}_{n,t}^{\pm} Y_{n,t}^{\pm} \right) + \mathrm{CAP}_{n,t}^{\pm}\, \mathrm{INV}_{n,t}^{\pm}\, Z_{n,t}^{\pm} \right] \tag{2ae}$$

subject to:

(1) Balance of energy carriers

(1a) Balance of natural gas

$$\sum_{i=1}^{2}\sum_{m=1}^{5} X_{i,1,m,t}^{\pm} + \sum_{m=1}^{7} X_{3,1,m,t}^{\pm} + \sum_{m=1}^{5} X_{4,1,m,t}^{\pm} + \left(\frac{\mathrm{Ele}_{1,t}^{\pm}}{\mathrm{Conv}_{1,t}^{\pm}} \right) \le \eta_{1,t}^{\pm} \mathrm{IMP}_{1,t}^{\pm}, \quad \forall t \tag{2af}$$

(1b) Balance of fuel oil

$$X_{1,2,1,t}^{\pm} + X_{1,2,3,t}^{\pm} + X_{1,2,4,t}^{\pm} + X_{2,2,1,t}^{\pm} + X_{2,2,3,t}^{\pm} + X_{2,2,4,t}^{\pm} + X_{2,2,6,t}^{\pm} + X_{3,2,5,t}^{\pm} + X_{3,2,6,t}^{\pm} + X_{3,2,7,t}^{\pm} + \sum_{m=1}^{6} X_{4,2,m,t}^{\pm} \le \eta_{2,t}^{\pm} IMP_{2,t}^{\pm}, \quad \forall t \tag{2ag}$$

(1c) Balance of LPG

$$X_{1,3,1,t}^{\pm} + X_{1,3,3,t}^{\pm} + X_{1,3,4,t}^{\pm} + X_{1,3,5,t}^{\pm} + X_{1,3,6,t}^{\pm} + X_{2,3,1,t}^{\pm} + X_{2,3,3,t}^{\pm} + X_{2,3,5,t}^{\pm} + X_{2,3,6,t}^{\pm} + X_{3,3,1,t}^{\pm} + X_{3,3,2,t}^{\pm} + X_{3,3,3,t}^{\pm} + X_{3,3,5,t}^{\pm} + \sum_{m}^{M}\sum_{t=1}^{T} X_{4,3,m,t}^{\pm} \le \eta_{3,t}^{\pm} \mathrm{IMP}_{3,t}^{\pm}, \quad \forall t \tag{2ah}$$

(1d) Balance of heating oil

$$X_{1,4,1,t}^{\pm} + X_{1,4,4,t}^{\pm} + X_{2,4,1,t}^{\pm} + X_{2,4,3,t}^{\pm} \le \eta_{4,t}^{\pm} \mathrm{IMP}_{4,t}^{\pm}, \quad \forall t \tag{2ai}$$

(1e) Balance of renewable energy resources

$$X_{1,5,1,t}^{\pm} + X_{1,5,2,t}^{\pm} + X_{1,5,4,t}^{\pm} + X_{1,5,6,t}^{\pm} + X_{2,5,1,t}^{\pm} + X_{2,5,3,t}^{\pm} + X_{2,5,6,t}^{\pm} + \sum_{m}^{M}\sum_{t=1}^{T} Rt_{4,5,t}^{\pm} X_{4,5,m,t}^{\pm} \le \mathrm{DREN}_{t}^{\pm}, \quad \forall t \tag{2aj}$$

(1f) Balance of electricity

$$\mathrm{EleNGA}_t^{\pm} + \mathrm{EleFO}_t^{\pm} + \mathrm{EleCOAL}_t^{\pm} + \mathrm{EleREN}_t^{\pm} \ge \sum_{n=1}^{N} (Y_{n,t}^{\pm}), \quad \forall t \quad (2ak)$$

(1g) Balance of diesel

$$X_{3,3,1,t}^{\pm} + X_{3,3,2,t}^{\pm} + X_{3,3,3,t}^{\pm} + X_{3,3,5,t}^{\pm} + X_{3,3,6,t}^{\pm} + \frac{Y_{4,t}^{\pm}}{\mathrm{Conv}_{4,t}^{\pm}} \le \eta_{5,t}^{\pm}\,\mathrm{IMP}_{5,t}^{\pm}, \quad \forall t \quad (2al)$$

(1h) Balance of jet fuel

$$X_{3,5,4,t}^{\pm} \le \eta_{6,t}^{\pm}\,\mathrm{IMP}_{6,t}^{\pm}, \quad \forall t \quad (2am)$$

(1i) Balance of gasoline

$$X_{3,6,1,t}^{\pm} + X_{3,6,2,t}^{\pm} + X_{3,6,3,t}^{\pm} + X_{3,6,5,t}^{\pm} + X_{3,6,6,t}^{\pm} \le \eta_{7,t}^{\pm}\mathrm{IMP}_{7,t}^{\pm}, \quad \forall t \quad (2an)$$

(1j) Balance of coal

$$X_{4,4,1,t}^{\pm} + X_{4,4,3,t}^{\pm} + X_{4,4,5,t}^{\pm} + X_{4,4,6,t}^{\pm} + \frac{Y_{3,t}^{\pm}}{\mathrm{Conv}_{3,t}^{\pm}} \le \eta_{8,t}^{\pm}\mathrm{IMP}_{8,t}^{\pm}, \quad \forall t \quad (2ao)$$

(2) End-user energy demand constraints

(2a) Space heating demands

$$\sum_{j=1}^{J} \mathrm{Con}_{i,j,t}^{\pm} X_{i,j,1,t}^{\pm} \ge \mathrm{DSH}_{i,t}^{\pm}, \quad \forall i, t\ i = 1 \text{ and } 2 \quad (2ap)$$

(2b) Space cooling demands

$$\sum_{j=1}^{J} \mathrm{Con}_{i,j,t}^{\pm} X_{i,j,2,t}^{\pm} \ge \mathrm{DSC}_{i,t}^{\pm}, \quad \forall i, t,\ i = 1 \text{ and } 2 \quad (2aq)$$

(2c) Water heating demands

$$\sum_{j=1}^{J} \mathrm{Con}_{i,j,t}^{\pm} X_{i,j,3,t}^{\pm} \ge \mathrm{DWH}_{i,t}^{\pm}, \quad \forall i, t, i = 1 \text{ and } 2 \quad (2ar)$$

(2d) Lighting demands

$$\sum_{j=1}^{J} \mathrm{Con}_{i,j,t}^{\pm} X_{i,j,4,t}^{\pm} \ge \mathrm{DLG}_{i,t}^{\pm}, \quad \forall i, t, i = 1 \text{ and } 2 \quad (2as)$$

(2e) Appliance energy demands

$$\sum_{j=1}^{J} \mathrm{Con}_{i,j,t}^{\pm} X_{i,j,5,t}^{\pm} \ge \mathrm{DAP}_{i,t}^{\pm}, \quad \forall i, t, i = 1 \text{ and } 2 \quad (2at)$$

(2f) Commercial ventilation demand

$$\sum_{j=1}^{J} \mathrm{Con}_{i,j,t}^{\pm} X_{i,j,4,t}^{\pm} \ge \mathrm{DVP}_{i,t}^{\pm}, \quad \forall i, t\ i = 2 \quad (2au)$$

(2g) Light duty vehicle energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,1,t}^{\pm} \ge \mathrm{DLD}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 1, 3, 4, 6 \text{ and } 7 \quad (2av)$$

(2h) Freight truck energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,2,t}^{\pm} \ge \mathrm{DFR}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 1, 3, 4, 6 \text{ and } 7 \quad (2aw)$$

(2i) Bus energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,3,t}^{\pm} \ge \mathrm{DBS}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 1, 3, 4, 6 \text{ and } 7 \quad (2ax)$$

(2j) Air plane demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,4,t}^{\pm} \ge \mathrm{DAR}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 5 \quad (2ay)$$

(2k) Recreational energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,5,t}^{\pm} \ge \mathrm{DRC}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 1, 3, 4, 6 \text{ and } 7 \quad (2az)$$

(2l) Railway energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,6,t}^{\pm} \ge \mathrm{DRL}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 1, 2, 4, 6, 7 \text{ for railway} \quad (2ba)$$

(2m) Equivalent lubricant energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,7,t}^{\pm} \ge \mathrm{DLB}_{i,t}^{\pm}, \quad \forall i = 3, t, j = 2 \text{ for lubricant} \quad (2bb)$$

(2n) Total electricity demand

$$\sum_{i=1}^{2}\sum_{m=1}^{5} X_{i,6,m,t}^{\pm} + \sum_{m=1}^{7} X_{3,6,m,t}^{\pm} + \sum_{m=1}^{5} X_{4,6,m,t}^{\pm} + \mathrm{EELE}_t^{\pm} \le \eta_{9,t}^{\pm} \sum_{n=1}^{N} Y_{n,t}^{\pm}, \quad \forall t \quad (2bc)$$

(2o) Agricultural energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,1,t}^{\pm} \ge \mathrm{DAGC}_{i,t}^{\pm}, \quad \forall i = 4, t, j = 1, 2, \ldots, 6 \quad (2bd)$$

(2p) Forest energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,2,t}^{\pm} \ge \mathrm{DFRO}_{i,t}^{\pm}, \quad \forall i = 4, t, j = 1, 2, 3, 5, 6 \quad (2be)$$

(2q) Mining energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,3,t}^{\pm} \ge \mathrm{DMIN}_{i,t}^{\pm}, \quad \forall i = 4, t, j = 1, 2, \ldots, 6 \quad (2bf)$$

(2r) Construction energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,4,t}^{\pm} \ge \mathrm{DCON}_{i,t}^{\pm}, \quad \forall i = 4, t, j = 1, 2, 3, 5, 6 \quad (2bg)$$

(2s) Pulp and paper energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,5,t}^{\pm} \ge \mathrm{DPP}_{i,t}^{\pm}, \quad \forall i = 4, t, j = 1, 2, \ldots, 6 \quad (2bh)$$

(2t) Manufacture energy demand

$$\sum_{j}^{J} \mathrm{Conv}_{i,j,t}^{\pm} X_{i,j,6,t}^{\pm} \geq \mathrm{DMAN}_{i,t}^{\pm}, \quad \forall i = 4, t, j = 1, 2, \ldots, 6 \tag{2bi}$$

(2u) Electricity export targets

$$\mathrm{EELE}_{t}^{\pm} \geq \mathrm{TARGET\_EX}_{t}^{\pm}, \quad \forall t \tag{2bj}$$

(3) Electricity generation facility capacity constraint

$$Y_{n,t}^{\pm} \leq \mathrm{EXCAP}_{n,t}^{\pm} + \mathrm{CAP}_{n,t}^{\pm} Z_{n,t}^{\pm} \tag{2bk}$$

$$\mathrm{Lower}\, Y_{n,t}^{\pm} \leq Y_{n,t}^{\pm} \leq \mathrm{Upper}\, Y_{n,t}^{\pm}, \quad \forall n, t \tag{2bl}$$

(4) GHG emission constraints

$$(4a) \sum_{i=1}^{I}\sum_{j=1}^{J} \mathrm{EmFt}_{1,i,j,t}^{\pm} \sum_{m=1}^{M} X_{i,j,m,t}^{\pm} \leq (\mathrm{EmCO_2})_{t}^{\pm} \tag{2bm}$$

$$(4b) \sum_{i=1}^{I}\sum_{j=1}^{J} \mathrm{EmFt}_{2,i,j,t}^{\pm} \sum_{m=1}^{M} X_{i,j,m,t}^{\pm} \leq (\mathrm{EmCH_4})_{t}^{\pm} \tag{2bn}$$

$$(4c) \sum_{i=1}^{I}\sum_{j=1}^{J} \mathrm{EmFt}_{3,i,j,t}^{\pm} \sum_{m=1}^{M} X_{i,j,m,t}^{\pm} \leq (\mathrm{EmN_2O})_{t}^{\pm} \tag{2bo}$$

where t = 1,2,. . .,5; $c_{1,1}$ = the total cost of natural gas (NGA) consumption in residential sub-sector; $c_{1,2}$ = the total cost of fuel oil (FO) consumption in residential sub-sector; $c_{1,3}$ = the total cost of liquefied petroleum gases (LPG) consumption in residential sub-sector; $c_{1,4}$ = the total cost of heating oil (HO) consumption in residential sub-sector; $c_{1,5}$ = the total cost of renewable energy (RE) resources consumption in residential sub-sector; $c_{1,6}$ = the total cost of electricity (ELE) consumption in residential sub-sector; $c_{2,1}$ = the total cost of NGA consumption in commercial sub-sector; $c_{2,2}$ = the total cost of FO consumption in commercial sub-sector; $c_{2,3}$ = the total cost of LPG consumption in commercial sub-sector; $c_{2,4}$ = the total cost of HO consumption in commercial sub-sector; $c_{2,5}$ = the total cost of RE consumption in commercial sub-sector; $c_{2,6}$ = the total cost of ELE consumption in commercial sub-sector; $c_{3,1}$ = the total cost of NGA consumption in transportation sub-sector; $c_{3,2}$ = the total cost of FO consumption in transportation sub-sector; $c_{3,3}$ = the total cost of LPG consumption in transportation sub-sector; $c_{3,4}$ = the total cost of diesel (DSL) consumption in transportation sub-sector; $c_{3,5}$ = the total cost of jet fuel (JF) consumption in transportation sub-sector; $c_{3,6}$ = the total cost of gasoline (GSL) consumption in transportation sub-sector; $c_{3,7}$ = the total cost of ELE consumption in transportation sub-sector; $c_{4,1}$ = the total cost of NGA consumption in industrial sub-sector; $c_{4,2}$ = the total cost of FO consumption in industrial sub-sector; $c_{4,3}$ = the total cost of LPG consumption in industrial sector; $c_{4,4}$ = the total cost of coal (CL) consumption in industrial sector; $c_{4,5}$ = total cost of RE consumption in industrial sector; $c_{4,6}$ = total cost of ELE consumption in industrial sector; n = electricity generation facilities (n = 1 = hydropower; n = 2 = coal; n = 3 = NGA; n = 3 = fossil fuel); $\eta_{1,t}^{\pm}$ = coefficient of loss; $\eta_{9,t}^{\pm}$ = line loss of electricity transportation.

Obviously, the above IEM model can effectively reflect: (i) interactions between a number of sub-sectors, technologies and energy resources among various energy management systems, (ii) uncertain information associated with input parameters that can be expressed as intervals, and (iii) the provincial baseline of energy management over the planning horizon. Thus, a series of decision related to "how and when to take adaptation actions toward climate change" can be obtained.

3. Method of solution

The method of solution is based on (a) the results of FIIM for climate change impact analysis, and (b) the interactive solution algorithm of ILP. Such an interactive solution algorithm has been developed to solve model (1) through analyzing the detailed interrelationships between parameters and variables and between the objective function and constraints. According to the algorithms, the solution for interval linear programming (ILP) model can be obtained through a two-step method, where a submodel corresponding to f^- (when the objective function is to be minimized) is first formulated and solved, and then the relevant submodel corresponding to f^+ can be formulated based on the solution of the first submodel. In detail, the first submodel can be formulated as follows (assume that $b_i^{\pm} > 0$, and $f^{\pm} > 0$):

$$\mathrm{Min}\, f^- = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^{n} c_j^- x_j^+ \tag{3a1}$$

subject to:

$$\sum_{j=1}^{k_1} |a_{ij}|^+ \mathrm{Sign}(a_{ij}^+) x_j^- + \sum_{j=k_1+1}^{n} |a_{ij}|^- \mathrm{Sign}(a_{ij}^-) x_j^+ \leq b_i^+, \quad \forall i \tag{3a2}$$

$$x_j^{\pm} \geq 0, \quad \forall j \tag{3a3}$$

where $x_j^{\pm}$, j = 1,2,. . .,k_1 are interval variables with positive coefficients in the objective function and $x_j^{\pm}$, $j = k_1 + 1, k_1 + 2, \ldots, n$ are interval variables with negative coefficients in the objective function. Thus, solutions of $x_{j\ \mathrm{opt}}^-$ (j = 1,2,. . .,k_1) and $x_{j\ \mathrm{opt}}^+$ ($j = k_1 + 1, k_1 + 2, \ldots, n$) can be obtained through solving submodel (3a). Then the submodel corresponding to f^+ can be formulated as follows (assume that $b_i^{\pm} > 0$, and $f^{\pm} > 0$):

$$\mathrm{Min}\, f^+ = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n} c_j^+ x_j^- \tag{3b1}$$

subject to:

$$\sum_{j=1}^{k_1} |a_{ij}|^- \mathrm{Sign}(a_{ij}^-) x_j^+ + \sum_{j=k_1+1}^{n} |a_{ij}|^+ \mathrm{Sign}(a_{ij}^+) x_j^- \leq b_i^-, \quad \forall i \tag{3b2}$$

$$x_j^{\pm} \geq 0, \quad \forall j \tag{3b3}$$

$$x_j^+ \geq x_{j\ \mathrm{opt}}^-, \quad j = 1, 2, \ldots, k_1 \tag{3b4}$$

$$x_j^- \leq x_{j\ \mathrm{opt}}^+, \quad j = k_1 + 1,\ k_2 + 2, \ldots, n \tag{3b5}$$

Solutions of $x_{j\ \mathrm{opt}}^+$ (j = 1,2,. . .,k_1) and $x_{j\ \mathrm{opt}}^-$ ($j = k_1 + 1, k_1 + 2, \ldots, n$) can be obtained through solving submodel (3b). Thus, we can have the final solution of $f_{\mathrm{opt}}^{\pm} = [f_{\mathrm{opt}}^-, f_{\mathrm{opt}}^+]$ and $x_{j\ \mathrm{opt}}^{\pm} = [x_{j\ \mathrm{opt}}^-, x_{j\ \mathrm{opt}}^+]$.

Thus, the integrated modeling system (IEMS) can be developed through linking the fuzzy-interval inference method (FIIM) and the inexact energy model (IEM). The general solution procedure for the proposed IEMS is presented in Fig. 5 and described as follows:

- **Step 1:** Identify climate change impacts on energy supply based on the obtained fuzzy sets;
- **Step 2:** Identify climate change impacts on end-user demand based on the obtained fuzzy sets;
- **Step 3:** Identify multi-layer, multi-sector and multi-period impacts of climate change on the EMS through the integration method;
- **Step 4:** Based on interval analysis and fuzzy sets theory, identify the integrated impact levels of climate change on the EMS;

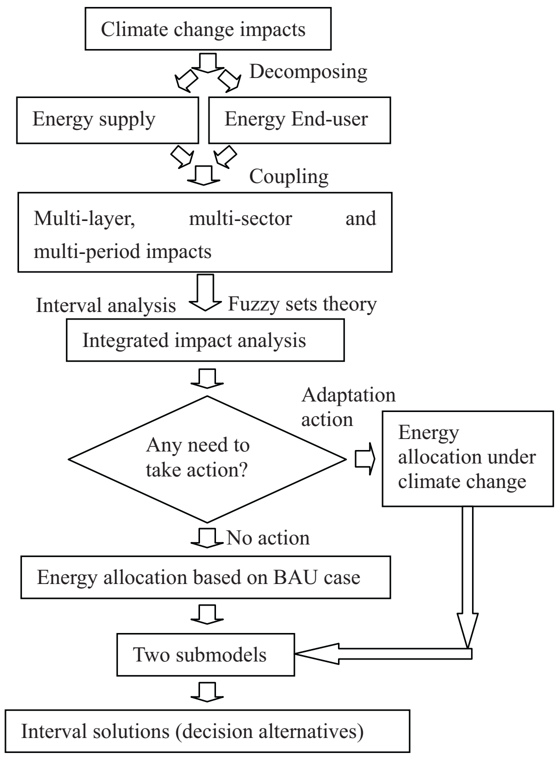

Fig. 5. Solution procedure.

- **Step 5:** Based on the integrated impact results and the values in Table 4, judge whether adaptation actions would be needed for the EMS under climate change;
- **Step 6:** If no adaptation actions would be needed, formulate the inexact model (IEM) under the BAU case;
- **Step 7:** Transform the IEM model into two submodels, where the lower bound of $f^{\pm}$ is first desired since the objective is to minimize $f^{\pm}$;
- **Step 8:** Formulate the f^{-} submodel, including the f^{-} objective function and the related constraints;
- **Step 9:** Solve the f^{-} submodel according to conventional LP (linear programming) solution methods, and obtain the solution for f^{-}_{opt} and $x^{-}_{i\ \text{opt}}$;
- **Step 10:** Formulate the f^{+} submodel, including the objective function and constraints corresponding to f^{+}, as well as the second set of constraints regulating the bounds of decision variables;
- **Step 11:** Solve the f^{+} submodel according to conventional LP (linear programming) methods and obtain the solution for f^{+}_{opt} and $x^{+}_{j\ \text{opt}}$;
- **Step 12:** The optimal results for the IEMS model can, thus, be obtained as $f^{\pm}_{\text{opt}} = [f^{-}_{\text{opt}}, f^{+}_{\text{opt}}]$ and $x^{\pm}_{j\ \text{opt}} = [x^{-}_{j\ \text{opt}}, x^{+}_{j\ \text{opt}}]$;
- **Step 13:** If adaptation actions need to be undertaken in responding to the integrated climate change impacts, formulate the corresponding model based on modeling structure formulated under the BAU case and the impact analysis results (i.e., the variations on energy supplies and demands) obtained from Steps 1 to 5;
- **Step 14:** Repeat Steps 7 to 12;
- **Step 15:** Make comparisons between results under the BAU case and climate change.

4. Conclusions

In this research, a large-scale integrated modeling system (IMS) was developed for supporting adaptation planning under impacts of climate change from an entire EMS point of view. A number of methodologies were seamlessly integrated into IMS, including the fuzzy-interval inference method (FIIM), inexact energy model (IEM), and uncertainty analysis. Compared to conventional studies in the similar areas, such a system could (i) incorporate multiple technologies, energy resources, and sub-sectors, and climate change impacts within a general modeling framework, (ii) address interactions of climate change impacts on multiple energy sub-sectors and resources within an EMS, (iii) identify optimal adaptation strategies of an EMS to climate change impact through a two-step procedure, (iv) deal with multiple levels of uncertain information associated with processes of climate change impact analysis and adaptation planning, and (v) seamlessly combine climate change impact analysis results with inexact adaptation planning. Thus, decision makers could have a comprehensive view on the EMS as well as the corresponding adaptation schemes under climate change, greatly improving the robustness and completeness of the decision-making processes. The developed method can be applied to long-term adaptation planning in energy management systems, particularly those that are highly dependent on renewable energy sources. The solutions can generate decision alternatives and thus help decision makers identify desired policies under climate change. In the companion paper, application of the developed approach will be conducted in the Province of Manitoba, Canada.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (51009004/E0901), the Major State Program of Water Pollution Control (2009ZX07104-004), and the Natural Sciences and Engineering Research Council of Canada (NSERC).

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